Argonne NATIONAL LABORATORY

ANL-ART-209

In-Sodium Testing of a Prototype Thermoacoustic Power Sensor for Sodium-Cooled Fast Reactors

Nuclear Science and Engineering Division

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In-Sodium Testing of a Prototype Thermoacoustic Power Sensor for Sodium-Cooled Fast Reactors

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September 28, 2020

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EXECUTIVE SUMMARY

The ultimate goal of this project is to develop and demonstrate a thermoacoustic power sensor (TAPS) for Sodium-Cooled Fast Reactors (SFRs), with potential application also envisioned to other nuclear technologies such as Lead-Cooled Fast Reactors (LFRs), Molten Salt Reactors (MSRs), in addition to Light Water Reactors (LWRs). The project was led by Westinghouse Electric Company, LLC (Westinghouse) and carried out in collaboration with Argonne National Laboratory (ANL) and the University of Pittsburgh. A TAPS is a passive (self-powered), non-invasive (wireless) sensor envisioned for measuring key parameters, such as local temperature and neutron flux, in a nuclear reactor core. The sensor generates pressure waves (i.e., sound waves) with a frequency and amplitude dependent upon nuclear operating conditions (coolant temperature or power changes). The acoustic waves are able to travel through the core and associated structures, and reach to the sensor network placed outside and/or inside of the reactor vessel. These sensors require a very small amount of power which, during loss of power events, can be provided, for example, by harvesting gamma radiation energy, thus resulting in a monitoring system that can function both during normal operation and during loss of power events.

Westinghouse and the University of Pittsburgh designed and fabricated TAPS prototypes for Argonne National Laboratory (ANL) to carry out in-sodium testing to evaluate the effects of sodium on the TAPS and the performance of the TAPS technique in sodium. Argonne received a TAPS prototype from Westinghouse, and the prototype was modified such that it can be installed into a test vessel and function in sodium at elevated temperature without potentially leaking. A water mockup test apparatus was constructed to validate proper working of the prototype. An instrumentation and control (I&C) system, running on the National Instruments (NI) LabView platform, was developed to: 1) operate both the water mockup test and the in-sodium test facility; and 2) process and analyze the received acoustic signals from an array of accelerometers and the Argonne sodium-submersible high-temperature acoustic sensor. The prototype was successfully tested in a water bath at different temperatures. Water mockup tests demonstrated that the TAPS prototype is working properly and its resonance frequency changes linearly with the coolant (water) temperature.

A TAPS test apparatus was constructed and integrated with the upgraded Under-Sodium Viewing (USV) sodium test facility. The integrated USV-TAPS sodium test facility has been operational. The TAPS prototype and a high-temperature sodium-submersible acoustic sensor (SSAS) developed by Argonne were both installed inside the TAPS test vessel. Being operated within argon cover gas under ambient conditions, the TAPS prototype demonstrated that it was functioning properly with a resonance frequency at 1407.2 Hz, which was successfully detected by the accelerometers mounted on the external wall of the vessel and the high-temperature SSAS installed inside the vessel.

After successfully transferring sodium into the vessel, in-sodium tests of the prototype were conducted. Tests of the TAPS prototype demonstrated that the resonance frequency of the TAPS changes linearly with respect to the temperature difference between the interior of the TAPS and bulk sodium. The early tests showed that the TAPS prototype could not establish a continuous and consistent resonance in sodium. The resonance diminished before the prototype reached its operating temperature. A signal postprocessor was added to the DAQ module latterly to isolate interferences, enhance signal conditioning, improve peak detection, and generate resonance frequency versus temperature plots. After testing in molten sodium and immersion at higher temperature for several weeks, the TAPS prototype was able to establish a continuous resonance.

Performance evaluation of the TAPS prototype was then conducted in sodium. The tests included the investigation of 1) the effects of the temperature difference between the TAPS and bulk sodium, 2) the effects of sodium flowrate; and 3) the performance of the different sensor-receiver systems positioned inside or outside the vessel. Results of a test demonstrated that, with limited sodium circulation, a continuous and consistent resonance of the TAPS prototype was established occasionally. The tests also demonstrated that, because of the nature of detection principles and mounting methods, the high-temperature SSAS is more affected by acoustic noise, while accelerometers are more affected by vibrations, in the test environment.

It is unknown why the TAPS prototype only occasionally established a continuous and consistent resonance when the TAPS temperature reached its operating temperature in molten sodium, and why it ultimately failed to resonate at all. A failure modes assessment was conducted and a few potential causes of failure were identified. Different post in-sodium tests were conducted to obtain additional information potentially relevant to the cause of the failure. Nondestructive evaluation techniques are suggested to examine the internal integrity as well as the gas mixture of the prototype. If they prove inconclusive, the prototype should be cut open to conduct a thorough inspection of its internal integrity and determine the state of the gas mixture.

Acknowledgments

Argonne is a U.S. Department of Energy Laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The work reported here was sponsored by the U.S. Department of Energy (DOE) Office of Nuclear Energy's Advanced Reactor Technologies (ART) program. The TAPS team would like to thank Mr. Christopher Grandy for his guidance and technical direction throughout the course of this effort. A special acknowledgement of thanks goes to Mr. Brian Robinson and Mr. Thomas Sowinski, Fast Reactor Program Managers for the DOE-NE ART program, during this work and to Dr. Robert Hill, the National Technical Director for Fast Reactors for the DOE-NE ART program, for their consistent support of the Advanced Concepts work. A special gratitude to our collaboration team, especially to Mr. Michael Heibel, Mr. Jorge Carvajal, and Dr. Paolo Ferroni of Westinghouse Electric Company, LLC, and Professor Jeffrey Vipperman of the University of Pittsburgh, for their crucial role of the design and fabrication of a TAPS prototype as well as valuable assistance and suggestions.

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Acronyms and Abbreviations

A/D	Analog-to-Digital
ANL	Argonne National Laboratory
ART	Advanced Reactor Technology
C&D	Control and Display
DAQ	Data Acquisition
DOE	U.S. Department of Energy
DOE-NE	Office of Nuclear Energy in the Department of Energy
FY	Fiscal Year
HT	High Temperature
I&C	Instrumentation and Control
ISHM	In-Sodium Hydrogen Meter
LFR	Lead-Cooled Fast Reactor
LWR	Light Water Reactor
MSR	Molten Salt Reactor
NI	National Instruments ™
SFR	Sodium-Cooled Fast Reactor
SSAS	Sodium-Submergible Acoustic Sensor
SMS	Signal Measuring System
SS	Stainless Steel
TAPS	Thermoacoustic Power Sensor
TC	Thermocouple
USV	Under-sodium Viewing

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1 INTRODUCTION

For operation optimization, cost efficiency, and safety, it is important to measure and monitor the operating conditions in real-time of a nuclear reactor core. The Thermoacoustic Power Sensor (TAPS) is a self-powered, wireless sensor that could be used for real-time, *in-situ* measurement of key parameters, such as local temperature and neutron flux, in a harsh environment, such as the reactor core of a Sodium-Cooled Fast Reactor (SFR), Lead-Cooled Fast Reactor (LFR), Molten Salt Reactor (MSR), in addition to Light Water Reactors (LWRs). The wireless TAPS is also applicable for *in-situ* temperature monitoring of dry casks for used fuel storage. TAPS is essentially a thermoacoustic engine that is encapsulated inside an instrumentation tube and heated by an integral nuclear-powered heater, for example, either a fuel pellet or a gamma-harvesting material. The instrumentation tube consists of a heat source (hot end), a ceramic stack, and an acoustic resonator (cold end) and is filled with a noble gas mixture. The acoustic (sound) waves, generated by the thermoacoustic effect, propagate through the reactor coolant and through the reactor core and associated structures, and then are measured by acoustic sensors located on the outside and/or inside of the reactor vessel. The wireless-transmitted acoustic signal is then amplified, filtered, and processed by a signal conditioning and data acquisition (DAQ) system. The sound wave amplitude corresponds to the local radiation flux in the core, and the resonance frequency is proportional to the local coolant temperature. The sensor array of TAPSs distributed throughout a reactor core is envisioned to provide wireless, real-time measurements of the local coolant temperature and neutron flux conditions as a function of position.

The ultimate objective of this project is to develop and demonstrate the TAPS technique for in-situ, real-time reactor power and core temperature monitoring of an SFR. For an SFR, the core inlet temperature and outlet temperature can vary from 350 and 500ºC, respectively, to 400 and 550ºC, respectively. The sodium temperature in testing should thus be varied over this range. In an SFR, there is an upward coolant flow over the fuel pins. If a TAPS is substituted for a fuel pin, then it will also be exposed to an upward coolant flow. Thus, a suitable upward sodium flow should be provided in testing. An SFR contains fuel pin, wirewrap, hexcan, and in-vessel structures. Ultimately, the effects of such structures should be simulated. However, in-sodium testing may be carried out without the structure, in order to characterize the TAPS output and signal transmission without the effects of intervening structures.

The current workscope includes five major tasks for in-sodium testing and performance evaluation of a TAPS prototype supplied by Westinghouse Electric Company, LLC (Westinghouse). This report documents the initial testing of the TAPS prototype in sodium. Section 2 lists the FY20 workscope and Section 3 reports the design and fabrication of a TAPS prototype. Section 4 documents the construction of the TAPS test apparatus and its integration with the Argonne USV sodium test facility. The TAPS test apparatus consists of a test vessel, a TAPS prototype, an accelerometer array, a high-temperature sodium-submergible acoustic sensor (SSAS), heating devices, a temperature control unit, and an instrumentation and control (I&C) unit.

Section 5 documents the performance evaluation of the TAPS prototype tested in molten sodium. After leak testing of the apparatus, the prototype and the SSAS, and an accelerometer array were successfully tested and verified working properly in the test vessel filled with cover gas. After sodium was introduced into the test vessel, the prototype was verified working properly, its resonance frequency was verified, and its onset points of thermoacoustic effects at different sodium temperatures and electric heater temperatures were evaluated. Section 6 presents the discussion and conclusions of the development and in-sodium testing of the TAPS technique for in-situ power/temperature measurement for an SFR. References cited in this report are then listed.

2 WORKSCOPE

The workscope for this project includes the following five major tasks proposed:

Tap Testing:

Tap testing was suggested by Westinghouse to identify the fully-coupled resonant frequencies of the vibroacoustic system constituted by the vessel, TAPS, fluid, vessel supporting structure, etc. This involves before and after introducing sodium to the vessel, using an impulse hammer to tap at designated input points on the vessel structure and nearby the accelerometers. The vibrational modes of the structural-acoustic system are expected to be temperature-dependent, and direct measurement allows for corroboration of the Finite Element Analysis (FEA) modeling of the vibrational modes, and post processing operational TAPS test data.

Signal Optimization:

This involves determining the optimal signal conditioning, including amplification, filtering, and processing according to the operating condition and resonance frequency range.

TAPS Prototype Verification:

After introducing sodium to the TAPS test vessel, using accelerometers and the Argonne high-temperature acoustic sensor to 1) verify that the TAPS prototype works properly, 2) verify resonance frequency of the TAPS prototype, and 3) determine the onset points of thermoacoustic effects at different sodium temperatures and electric heater temperatures (or input power).

In-Sodium Pilot Testing and Performance Evaluation

The task includes the evaluation of the sensitivity, response time, and reproducibility of the TAPS prototype under different power settings of the electric heater, different sodium flowrates, and different sodium temperatures. The prototype was to be tested without and with the pump with the sodium temperature ramped up and down between 200°C and 343°C (392°F and 650°F).

Sensor Optimization

Based on results of the in-sodium pilot testing, Argonne will conduct a sensor optimization to recommend, for example, the optimal resonance, a calibration procedure (if needed), and the optimal operating conditions for the development of a TAPS array that is applicable for its implementation in an SFR.

3 DESIGN AND FABRICATION OF TAPS

This section provides a brief introduction to physics, design, and potential benefits of TAPS technology when applied to nuclear reactors. A history of the research and development of the TAPS technique and the mathematical description of TAPS basic principles were described in a previous report [1]. TAPS technology serves as a mechanism to convert thermal energy to acoustic energy. TAPS is essentially a thermoacoustic engine that is encapsulated inside an instrumentation tube, i.e. an acoustic resonator. It internally consists of a heat source (hot end), a ceramic stack, and an acoustic resonator (cold end), and is usually filled with a noble gas mixture [2]. For consistent heating and better reproducibility, a TAPS usually uses a passive nuclear-powered heating source, for example, either a fuel pellet or a gamma-harvesting material which eliminates the use of any electric wires and enables the sensor to be wireless, as well as extends the life expectancy of the sensor. When heat is introduced to a TAPS at the hot end, the heat is transferred by electromagnetic (EM) radiation to the stack located in between the hot and cold ends of the TAPS. Because of the temperature gradient between the hot and cold ends, larger-scale molecular motion of the filled gas then oscillates across the stack and produces standing thermoacoustic waves that ultimately "ring out" at its acoustic natural frequencies. The acoustic waves will then propagate through the reactor coolant (sodium) and through the reactor core structure, and are measured by acoustic sensors located on the outside of the reactor vessel. The wireless-transmitted acoustic signal is then amplified, filtered, and processed by a signal conditioning and data acquisition (DAQ) system. The sound wave amplitude corresponds to the local radiation flux in the core, and the wave frequency is proportional to the local coolant temperature. An array of TAPSs distributed throughout a reactor core is envisioned to provide wireless, real-time measurements of the local coolant temperature and neutron flux conditions as a function of position.

In conjunction with exploration of the SFR application, Westinghouse developed a full set of functional requirements for the (1) TAPS sensor hardware, (2) TAPS Signal Measurement System (SMS) hardware and software, and (3) the TAPS testing program [3]. Based on the mathematical model of thermoacoustic effects and the requirements for in-sodium testing at the Argonne Under-Sodium Viewing (USV)-TAPS facility, Westinghouse designed a TAPS prototype for in-sodium testing in the USV facility [2]. For laboratory pilot testing, an electrical heater was used to simulate the passive heating device. Its housing was also modified for easy installation or remove. Figure 1 shows sketches of the TAPS Assembly design for sodium application, which proceeded as an evolution of the original hardware developed for a synergistic LWR program [1]. In addition, the improvements included a thermal core with improved efficiency and simpler, more robust fabrication methods. The prototype consists of eight main components: TAPS shell, ceramic stack, electrical heater, isolation springs, insulation cap, slotted tubing, holding assembly, and thermocouple (TC). The specifications and details of the components were reported in Ref. 2. Figure 2 shows a photograph of a TAPS prototype manufactured by Mirion IST for in-sodium performance evaluation.

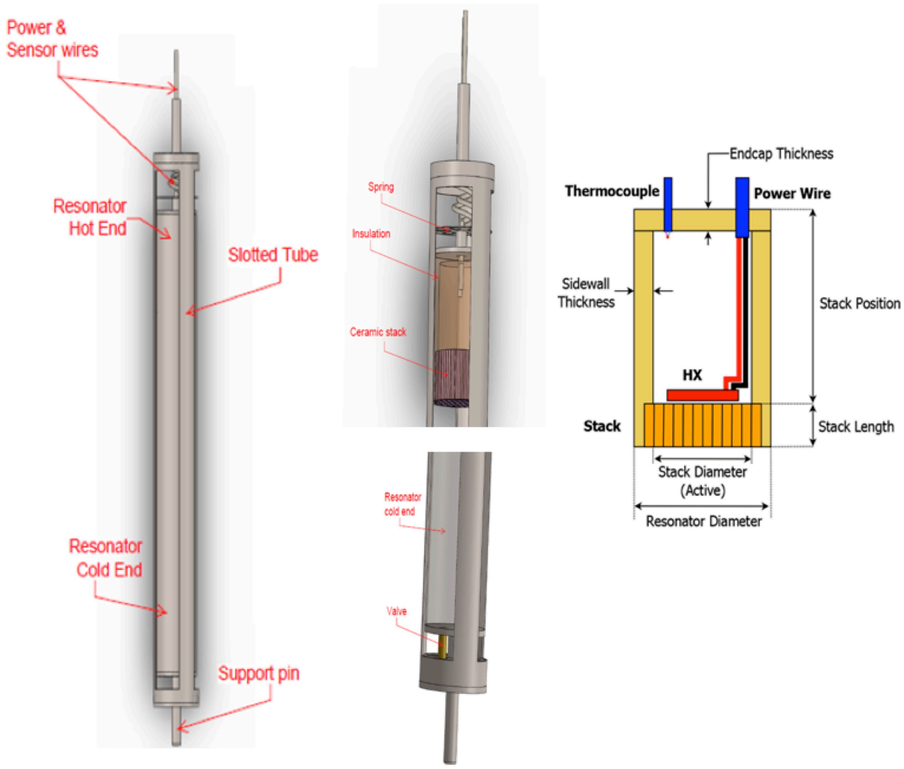


Figure 1. Sketches of the TAPS Assembly design: (left) resonator; (top-right) hot end; (bottom-right) cold end [1].

Figure 2. Photograph of TAPS prototype for in-sodium performance evaluation.

4 INTEGRATED USV-TAPS SODIUM TEST FACILITY

The TAPS, developed by Westinghouse, potentially could be used for real-time core temperature/power monitoring of an SFR. To demonstrate the TAPS technique in a sodium environment, a TAPS test apparatus was designed and constructed in FY19 [2]. This section documents the integration of the TAPS test apparatus with the Argonne USV sodium test facility for in-sodium tests of a TAPS prototype supplied by Westinghouse.

4.1 Design of Integrated USV-TAPS Sodium Test Facility

The USV sodium test facility was modified to accommodate the new TAPS and In-Sodium Hydrogen Meter (ISHM) test apparatuses. To be operated independently, both test apparatuses were branched from the USV sodium loop. The TAPS test apparatus consists of four major units: TAPS test vessel, temperature control module, acoustic sensor array, and I&C unit. Figure 3 shows a diagram of the integrated USV-TAPS sodium test facility.

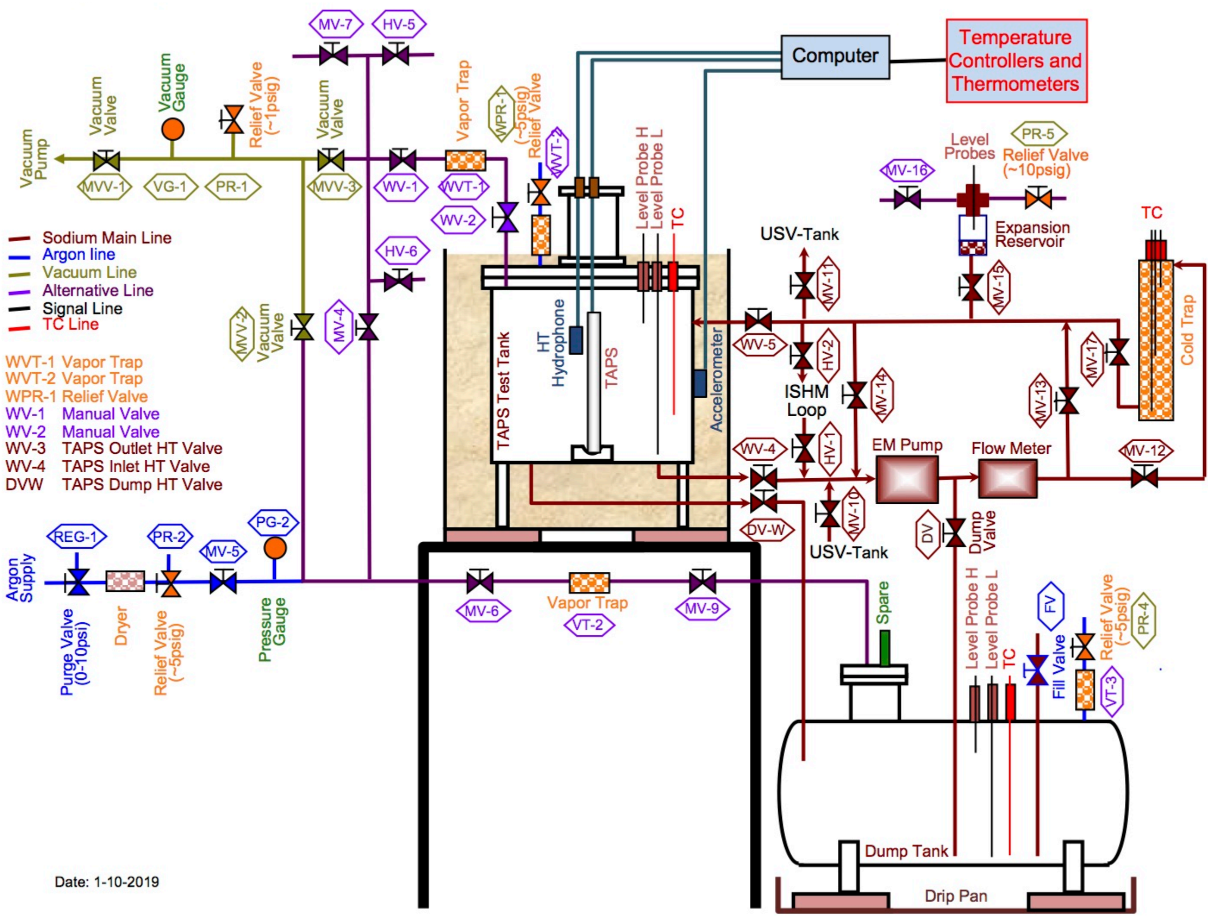


Figure 3. Diagram of integrated USV-TAPS sodium test facility.

<u>*TAPS Test Vessel*</u>:

The TAPS test vessel, 12" in diameter and 19.5” in height, was built and tested according to ASME Code Section VIII and is ASME Code stamped to be operated up to 343°C (650°F) and 30 psig. This is the same temperature to which the TAPS-USV facility is approved to operate. The TAPS test vessel consists of a high temperature (HT) sodium filling/dumping valve, two shut-off valves for sodium input and output, and a top flange assembly. Through the two shut-off valves, the apparatus can be used to control a test under isolated or pumped flow mode, or isolated from the USV sodium loop for service.

The top flange assembly of the vessel consists of a cover flange, an extension cap, a cap cover flange, and six feedthroughs for sodium level probes, K-type thermocouple (TC), pressure relief valve, and cover gas/vacuum line. The three conductive level sensors, sealed by a graphite compression seal, fed through the cover flange, are set for low, fill, and high. The TAPS prototype is installed through the top cover flange and the extension cap, which allows the prototype to be lifted out of the liquid sodium and removed from the test vessel without sodium draining nor opening the cover flange that might cause sodium contamination. Figure 4 shows a diagram of the dimensions of the test vessel and the setup of a TAPS prototype inside the vessel.

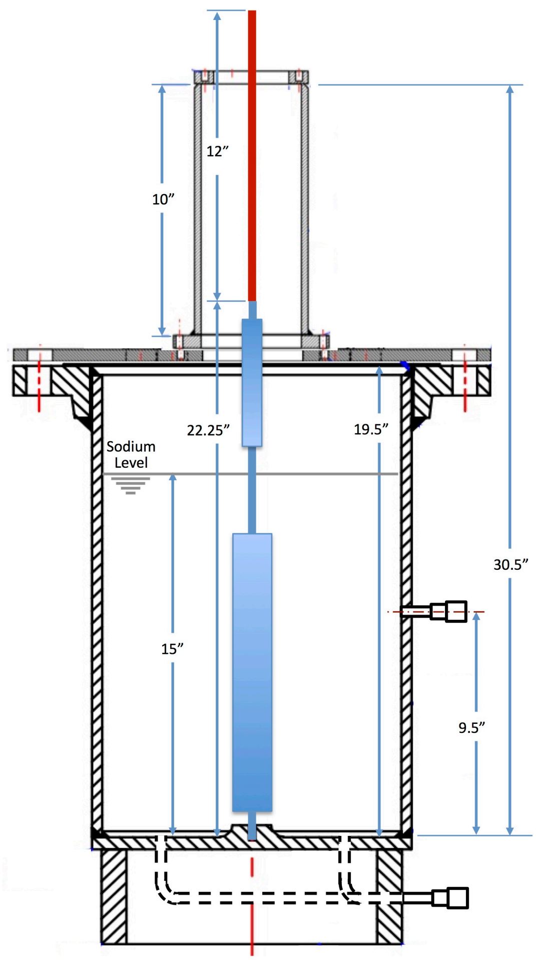


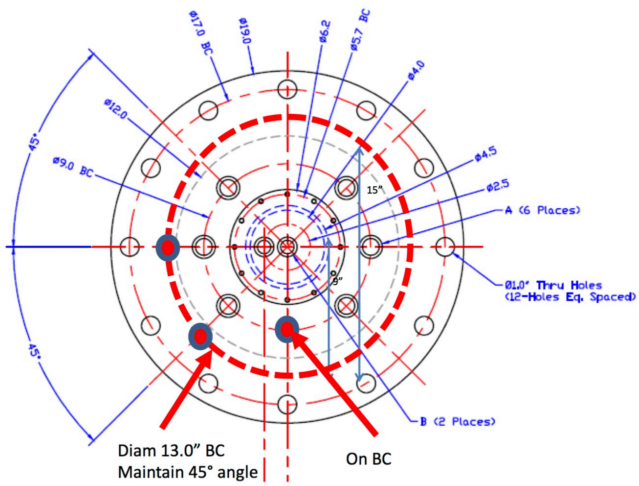
Figure 4. Diagram of TAPS test setup.

Temperature Control Module:

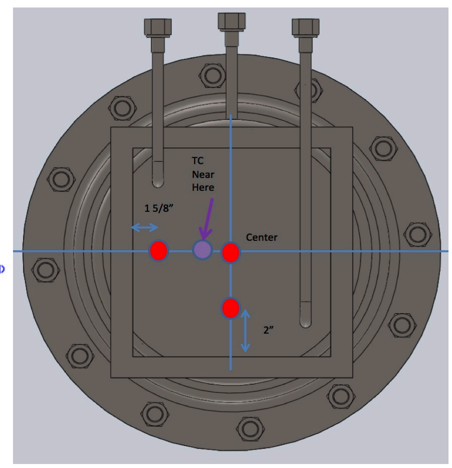
A temperature control module was constructed to control and monitor the sodium temperature in the test vessel and pipelines, and the internal temperature of the TAPS prototype. Fiberglass trace heaters (HTS/Amptek, up to 900°F) are mounted on the outer walls of the vessel body and all the pipelines and valves. Each is controlled and monitored by a PID temperature controller (HTS/Amptek Model BBA-200), respectively. The internal heater of the TAPS prototype is controlled by a variable linear DC power supply (VOLTEQ Model HY3005D-3) for a precise continuous adjustment.

Acoustic Sensor Array:

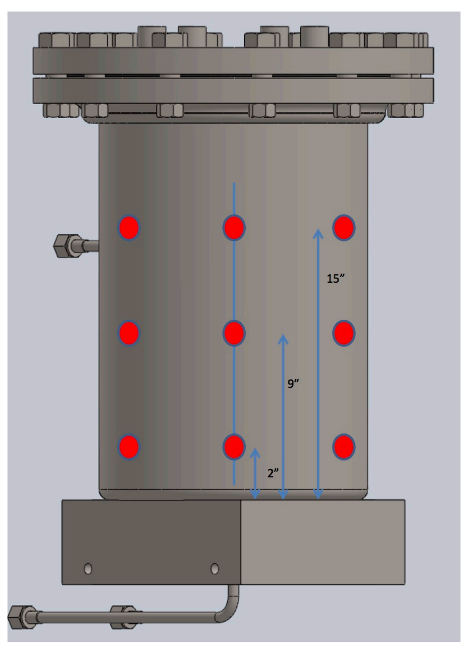
An array of accelerometers and a high-temperature SSAS are used to monitor the resonance frequency generated by the TAPS prototype. For optimal signal reception or sensor sensitivity, ten accelerometers (PCB 357B61) were mounted on the external wall of the vessel body, bottom, and top flange at designed locations according to the modelling conducted by the University of Pittsburg, to measure the acoustic resonance generated by the TAPS prototype. A high-temperature SSAS developed at Argonne was inserted into the sodium through a feedthrough on the top flange. Figure 5 shows the mounting locations of the ten accelerometers.



(a) Flange



(b) Bottom



(c) Body

Figure 5. Mounting locations of accelerometers.

Instrumentation and Control Unit:

An instrumentation and control (I&C) unit was developed to operate the integrated USV-TAPS sodium test facility. The system consists of four major modules: flow control, signal conditioning, DAQ, and control and display (C&D). The functionalities of the three modules are described as the following:

- Flow control module: This module controls and monitors the sodium flow during an in-sodium test under the pumped flow mode. It consists of an EM sodium pump (CMI Novacast Model CA-15) to generate a sodium flowrate up to 5 gal/min and an EM sodium flowmeter (CMI Novacast Model FS-15) to monitor sodium flowrate. The TAPS apparatus is isolated from the USV sodium loop when tested under stagnant mode. Under the pumped flow mode, molten sodium is circulated through the USV-TAPS sodium loop by the EM pump.
- Signal conditioning: This module measures, amplifies, and filters the received acoustic signals (i.e. the resonance frequency) generated by the TAPS and detected by the sensor array (accelerometers and acoustic sensor) before feeding to DAQ module. Table 1 lists the signal conditioning instruments used for in-sodium TAPS testing.
- DAQ module: This model consists of an eight-channel compactDAQ unit (NI Model cDAQ 9178) and a DAQ computer. After signal conditioning, each received acoustic signal is fed to an analog-to-digital (A/D) converter unit (NI Model 9215), respectively. The temperatures of the TAPS probe and the sodium within the test vessel are also measured by K-type thermocouples, respectively, and digitized by a TC unit (NI Model 9213). The compactDAQ unit then transfers the digitized acoustic signals and temperatures to the DAQ computer, which processes and analyzes the received acoustic signals, then obtains the acoustic amplitude and resonance frequency of the TAPS probe at the operating (sodium) temperature. The DAQ instruments are also listed in Table 1.

Table 1: Instrumentation list of in-sodium TAPS test

Name	Model	Specifications
Charge Accelerometer	PCB 357B61	10 pico-Columbus (pC) per gram, T_{max}: 482°C/900°F, 5 KHz
In-line Charge Converter	PCB 422E36	10 mV/pC, ±2.5 V, 121°C/250°F
Charge Amplifier	PCB MOD 462A	
Dual Filter	DL 4302	Dual 24 dB/octave, 10 Hz – 1 MHz
Sensor Signal Conditioner	PCB 483C41	8 Channels, Sensor: ICP®, Charge, Voltage
Eight-Slot USB Chassis	NI cDAQ 9178	0 – 10 MHz
Analog Input Module	NI 9215	4 AI, ±10 V, 16 Bit, 100 kilo-samples per second per channel simultaneous
Thermocouple Module	NI 9213	16 TC, ±78 mV, 24 Bit, 75 samples per second Aggregate
DC Power Supply	VOL TEQ HY3005D-3	Dual Channels, 0 – 30 VDC, 0 – 5 A

Control and Display (C&D) module: This module controls and displays the operating parameters of the TAPS frequency analysis as well as of the NI A/D converting units used in the DAQ module, such as channels and data acquisition rate (delay). The module then displays the acoustic spectrogram of the TAPS with respect to it temperature. Figure 6 shows a screenshot of the C&D panel of the I&C unit running on LabView® platform. The top-left of the panel shows the DAQ control of the NI units and their operating parameters; top-right shows temperatures of sodium in the test vessel and electric heater of the TAPS; bottom-left shows spectrum of the received acoustic signal and TAPS resonance frequency; and bottom-right shows the spectrogram. Spectrum and spectrogram of the SSAS and seven accelerometers can be displayed by changing the input signal selection.

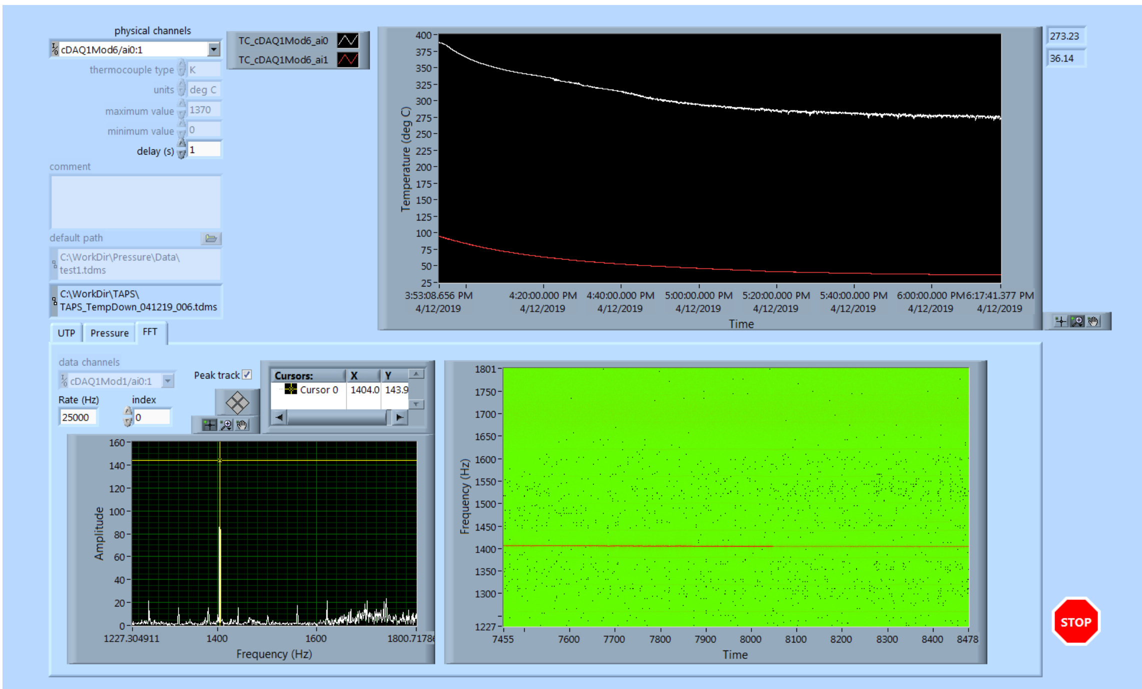


Figure 6. Control and display (C&D) panel of the TAPS I&C system: (top-left) DAQ control; (top-right) sodium and TAPS temperatures; (bottom-left) spectrum; (bottom-right) spectrogram.

4.2 Construction of Integrated USV-TAPS Sodium Test Facility

The integrated USV-TAPS sodium test facility was constructed and is located in the Building 308 High-Bay at Argonne. The TAPS test vessel was placed in a stainless steel (SS) secondary container (28.5” width ×30” diameter ×30.5” height). VCR fittings are used between all the connections that would be in contact with molten sodium. Unplated nickel gaskets (NI-8-VCR-2-VS or NI-8-VCR-2-GR-VS) are used for all the VCR fitting connections supplied by Swagelok. All the valves that would be in contact with molten sodium are bellows-sealed valves welded with VCR fitting end connections supplied by Swagelok (SS-8UW-HT-V47) of 480 psig @1,200°F (648°C). Fiberglass trace heaters (HTS/Amptek, up to 900°F) are mounted on the outer walls of the vessel body and all the pipelines and valves. PID temperature controllers (HTS/Amptek Model BBA-200) are used to control and monitor the temperatures of the test vessel and pipelines. Figure 7 shows a photograph of the integrated USV-TAPS sodium test facility, before piping insulation, with an ISHM test apparatus that is being added on the left side.

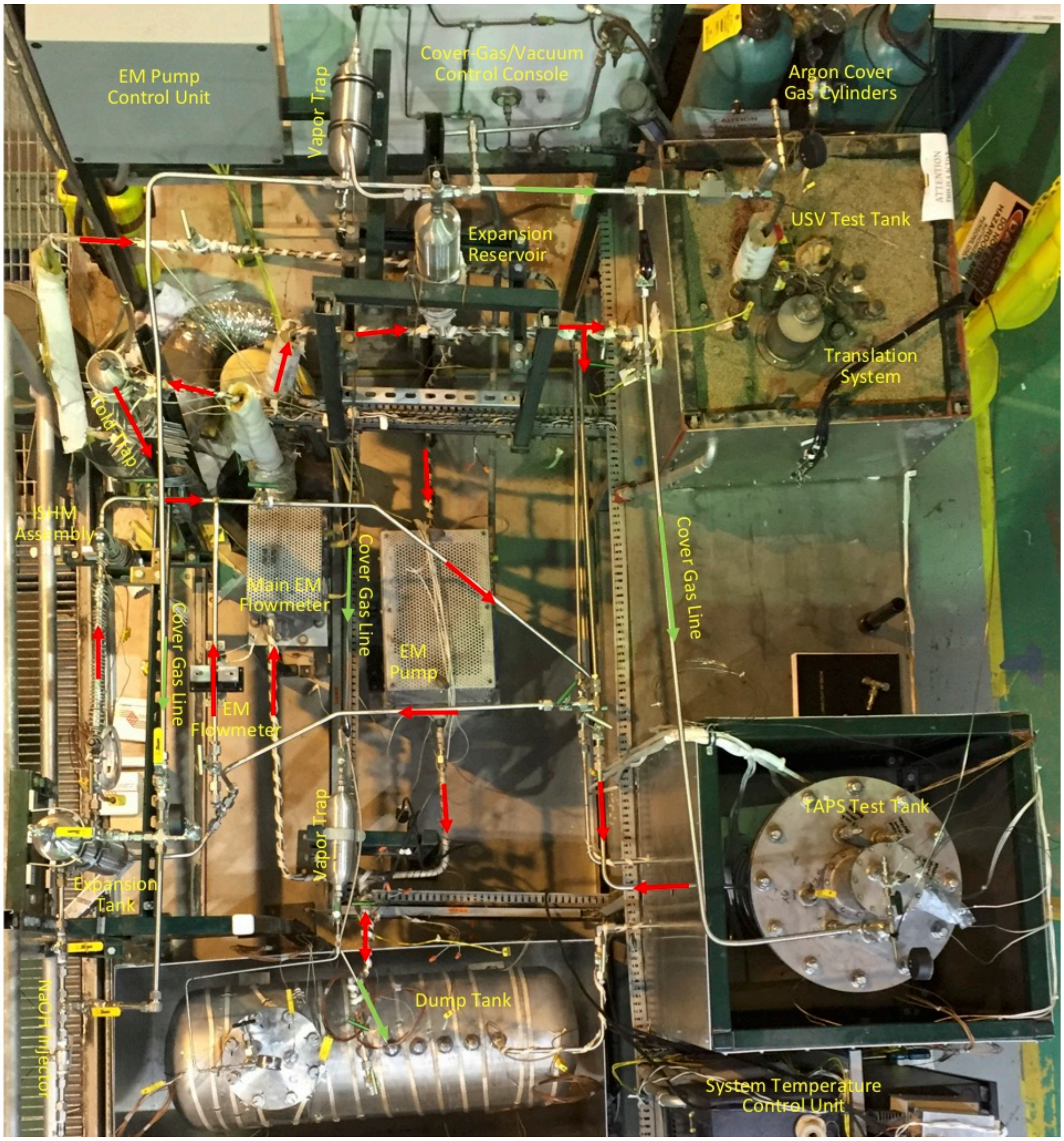


Figure 7. Photograph of integrated USV-TAPS sodium test facility.

4.3 Installations of Sensor Array and TAPS Prototype

A pin was welded at the bottom of the TAPS prototype for sensor alignment and support to avoid potential vibration caused by sodium flow. The TAPS prototype was then installed into the test vessel through the center feedthrough on the cover cap flange of the top flange assembly. The setup of a TAPS prototype inside the test vessel was shown in Figure 4. Level sensors, TCs, and SSAS were also installed through the feedthroughs on the cover flange. To minimize the probability of modal influences between the resonances of the TAPS and the test vessel, ten accelerometers with stainless steel (SS) mounting bases were mounted at the designated locations (Figure 5) suggested by the modal analysis conducted by the University of Pittsburg. Trace heaters were then mounted on the test vessel. Figure 8 shows a photograph of the setup of the TAPS test vessel. The TAPS test apparatus was sealed and leak-tested to hard vacuum. After filling the secondary containment with vermiculite, the apparatus was baked out at 250°C under vacuum.

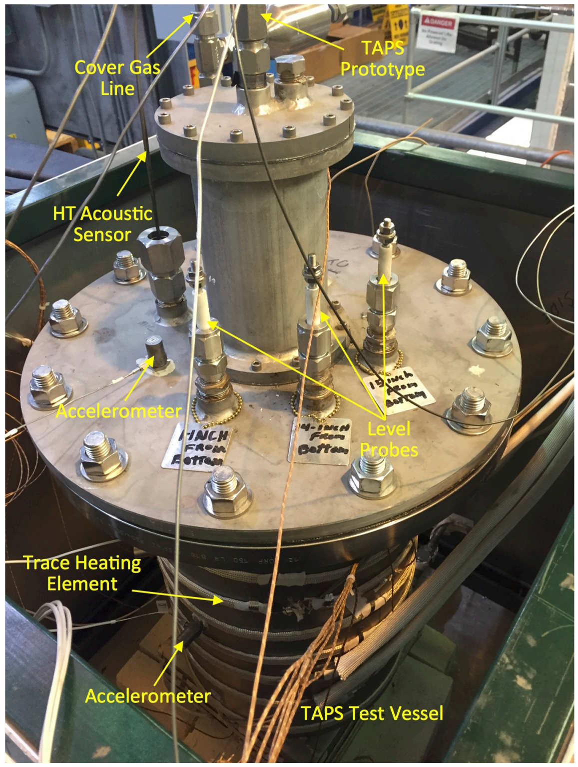


Figure 8. Photograph of TAPS test setup.

5 IN-SODIUM TESTING OF THE TAPS PROTOTYPE

The TAPS, developed by Westinghouse, potentially could be used for real-time core temperature/power monitoring of an SFR. This section documents the in-sodium testing and performance evaluation of a TAPS prototype in a sodium environment. The operating temperature, i.e. the operating resonance frequency, of a TAPS is determined by its heating source, which is consistently set at a designated level. When reaching its designated operating temperature, the prototype then establishes a continuous resonance. The resonance frequency will shift linearly with the temperature change of the cold end of the prototype, i.e. the coolant temperature. Before and after sodium was introduced into the test vessel, tests were successfully conducted to verify if the TAPS prototype and the high-temperature SSAS were working properly, as well as to optimize the signal conditioning and DAQ setups. In-sodium tests of the prototype were then conducted.

5.1 Verification of TAPS Prototype

After being inserted into the TAPS test vessel and before introducing sodium into the vessel, preliminary tests of the TAPS prototype were conducted to verify that the TAPS prototype and the SSAS were operating properly. The tests also determined the setups of the I&C unit for signal conditioning and DAQ optimizations for TAPS in-sodium testing. After leak testing of the apparatus, the prototype and SSAS were tested with the test vessel filled with cover gas under ambient conditions. The test demonstrated that the accelerometers and the SSAS both measured the TAPS resonance frequency at 1,407.2 Hz and confirmed that they were working properly. Figure 9 shows the spectrogram of the prototype detected by the SSAS inside the test vessel filled with cover gas under ambient conditions. The TAPS was able to generate a continuous and consistent resonance at 1407.2 Hz when the prototype was operated at 590°C continuously.

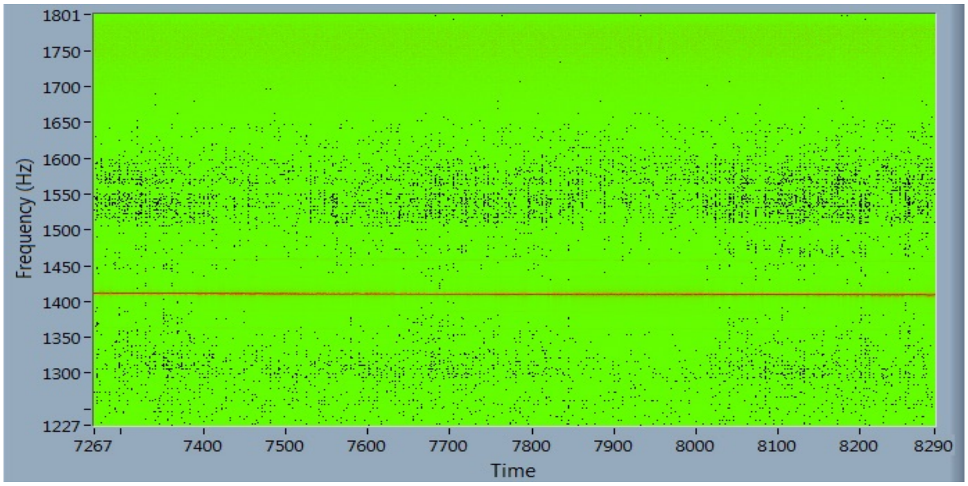


Figure 9. Spectrogram of the TAPS acquired by SSAS in cover gas under ambient conditions.

After introducing sodium to the TAPS test vessel, accelerometers and the Argonne high-temperature SSAS were used to 1) verify that the TAPS prototype works properly, 2) verify resonance frequency of the TAPS prototype, and 3) determine the onset points of thermoacoustic effects at different sodium temperatures and electric heater temperatures (or input power). The prototype was tested in sodium at a sodium temperature of 76.8°C with the DC power supply set at 13.1V and 4.93A. The SSAS and all seven accelerometers were tested and confirmed working properly. Figure 10 shows a spectrogram acquired by the SSAS for testing in sodium. It shows onset of resonance of the prototype at 1,213.2Hz, when the temperature of the TAPS hot-end reached 199.4°C. The resonant frequency increased to 1,256.5Hz, when the temperature of the TAPS hot-end reached 527°C.

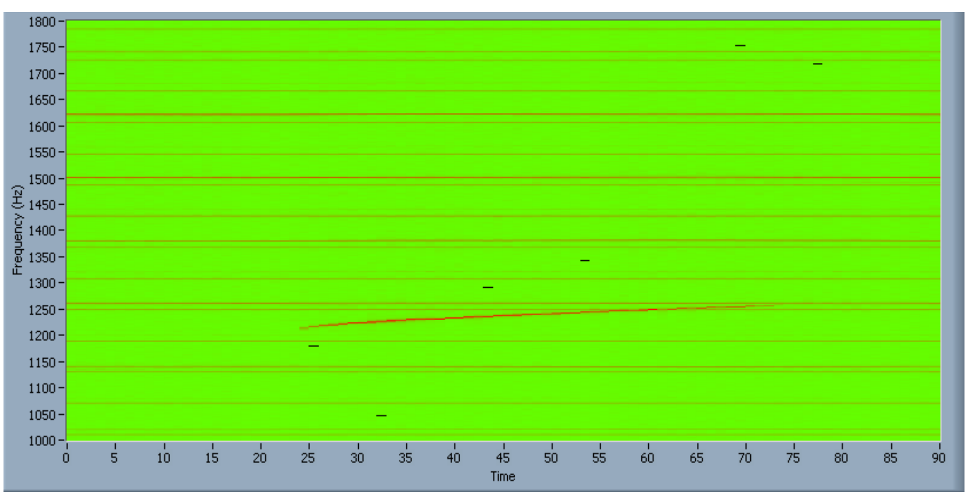


Figure 10. Spectrogram of the TAPS acquired by SSAS in sodium at 76.8°C.

5.2 In-Sodium Prototype Testing and Performance Evaluation

In-sodium tests of the TAPS prototype were conducted to evaluate the stability and performance of a TAPS operated in a sodium environment. The TAPS test apparatus has two HT shut-off valves for sodium input and output that are used to isolate the apparatus from the USV sodium loop. While running under the isolated unpumped mode, the TAPS test vessel was isolated from the USV sodium loop with these two valves shut off.

According to analysis, the resonant frequency of a TAPS shifts linearly with the change of the temperature difference between the hot side (heating temperature) and cold side of the ceramic stack. A TAPS prototype, fabricated and supplied by Westinghouse, was installed into the TAPS test vessel for in-sodium testing and performance evaluation. An array of accelerometers and a high-temperature SSAS were used to measure the acoustic resonance generated by the TAPS prototype.

5.2.1 In-Sodium Test of TAPS in Solid Sodium

The prototype was first tested in solid sodium at a bulk temperature 76.8°C as measured by the TC inside of the test vessel with the DC power supply set at 13.1V and 4.93A. Figure 10 shows a spectrogram, acquired by the SSAS, of the TAPS prototype in sodium at 76.8°C. It shows that the resonance of the prototype was first measured at 1,213.2Hz when its temperature measured by the TC inside the hot end of the TAPS reached 199.4°C, and increased to 1,256.5Hz when reaching 527°C. The resonant frequency of the TAPS prototype was lower than that (1,420Hz) in the cover gas test. No harmonics were detected at higher frequencies.

Unlike the clean background in cover gas test shown in Figure 9, in-sodium testing showed that there is strong electromagnetic interference (EMI) and/or systematic harmonics from the environment. A signal postprocessor was added to the DAQ module to isolate interferences, enhance signal conditioning, improve peak detection, and generate resonance frequency versus -temperature plots. Figure 11 shows an improved spectrogram of the acoustic signal detected by the SSAS after postprocessing with spectral subtraction, band-pass filtering, and peak follower and gating methods. Figure 12 shows that the TAPS resonance frequency changes with respect to the temperature difference between TAPS and sodium.

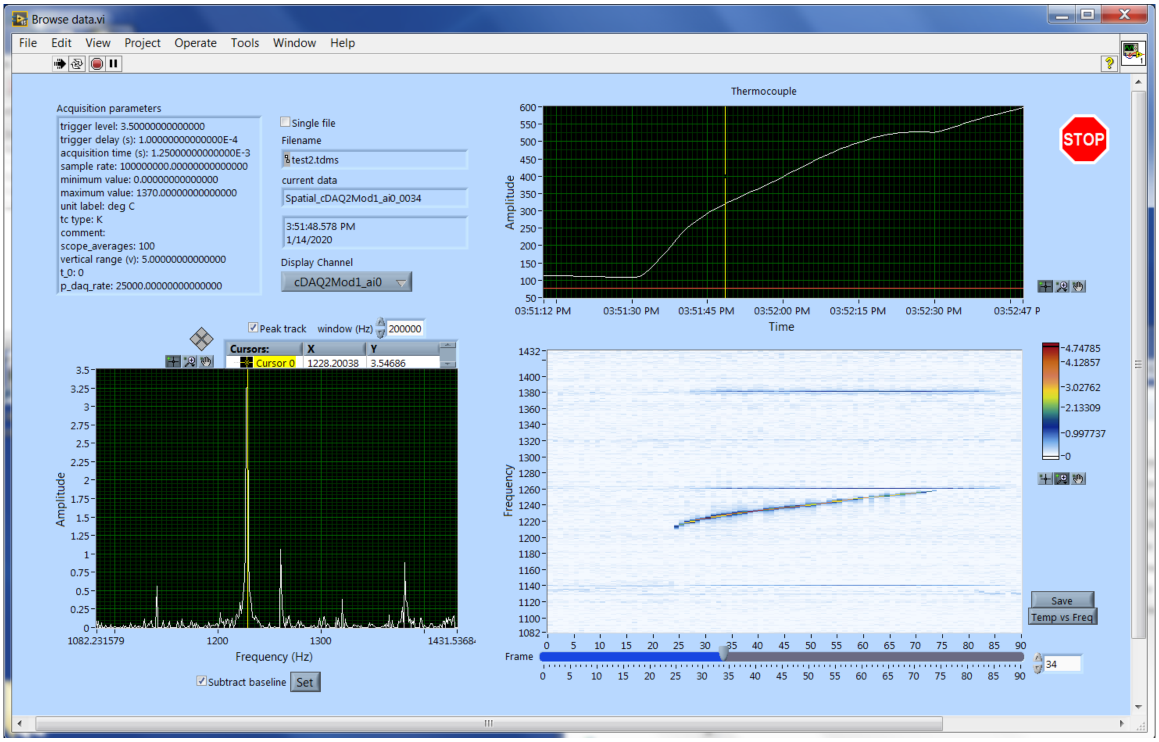


Figure 11. Bulk sodium and TAPS temperatures (top right), spectrum (bottom left), and spectrogram (bottom right) acquired by SSAS in sodium after postprocessing.

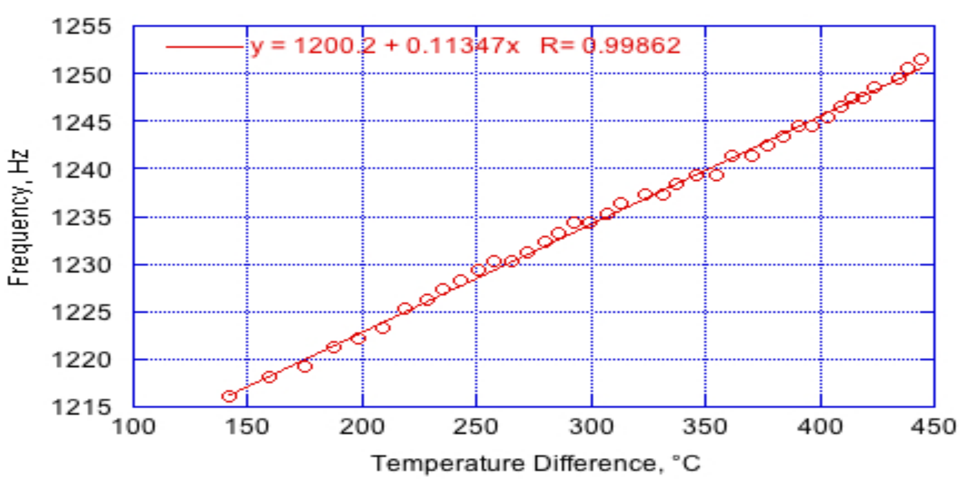


Figure 12. Resonance frequency with respect to temperature difference between TAPS and bulk sodium in sodium at 76.8°C.

Seven of the ten accelerometers mounted on the test vessel were selected along with the SSAS submerged in the sodium. Figure 13 shows the postprocessed spectrograms, acquired by the SSAS and the seven accelerometers, of the TAPS prototype tested in sodium. All of them show similar results of the TAPS resonance frequency shifting with respect with its hot end temperature. The test verified that the TAPS prototype, the seven accelerometers, and the SSAS all were working properly. Accelerometers # 3, #5, and #6 received strong low-frequency EMIs and #3 also received periodic wide-band noise.

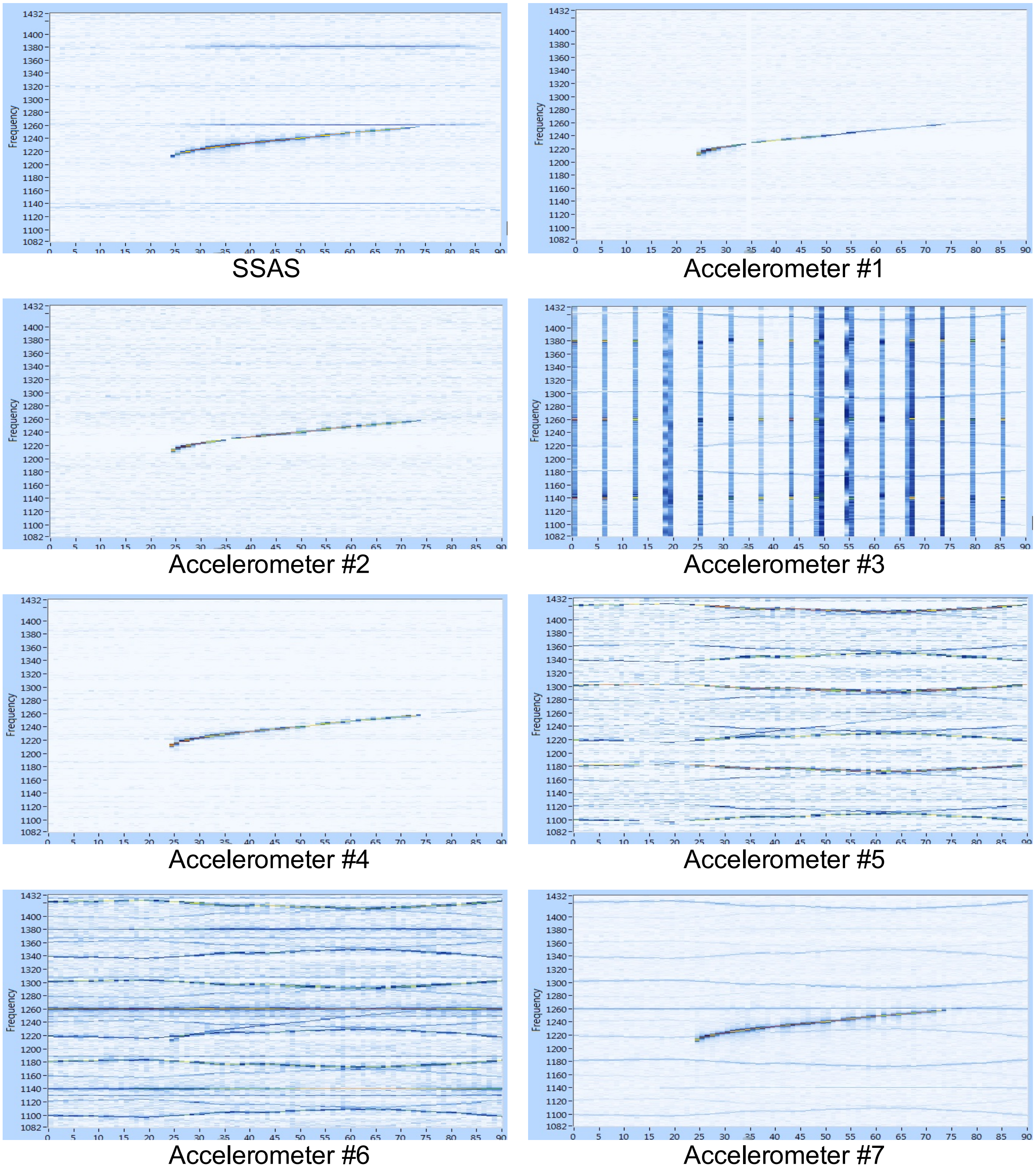


Figure 13. Postprocessed spectrograms acquired by SSAS and accelerometers in sodium at 76.8°C.

The TAPS prototype was then tested in solid sodium at 45.2°C with the DC power supply set at 13.2V and 4.9A. Figure 14 shows sensor and sodium temperatures, spectrogram, and spectrum of the TAPS acquired by the SSAS. The spectrogram was generated in real-time with background subtraction, which reduced the background interference greatly. Figure 15 shows a plot of the TAPS resonance frequency changing with respect to the temperature difference between the TAPS and bulk sodium.

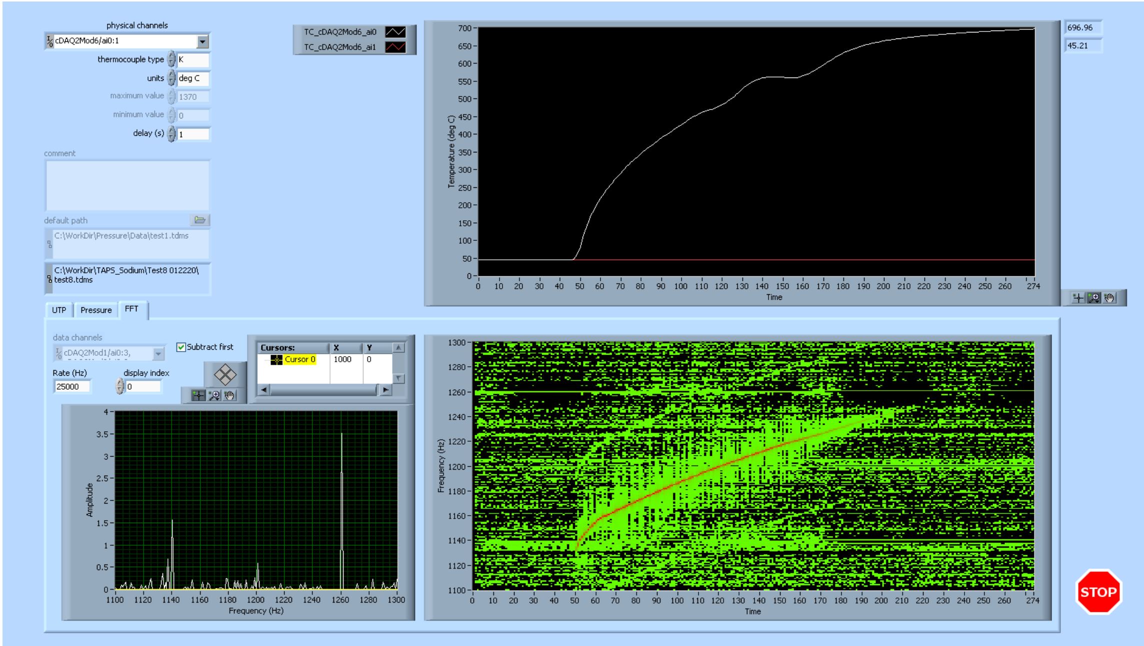


Figure 14. Sodium and TAPS temperatures (top right), spectrum (bottom left), and spectrogram (bottom right) of the TAPS acquired by SSAS in sodium at 45.2°C.

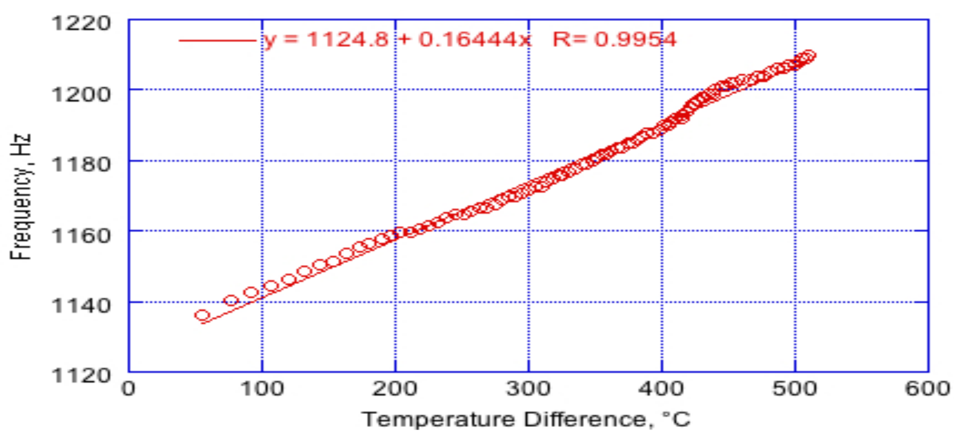


Figure 15. Resonance frequency versus temperature difference between TAPS and bulk sodium in solid sodium at 45.2°C.

Figure 16 shows the postprocessed spectrograms, acquired by the SSAS and the seven accelerometers. Accelerometer #1 shows minimum EMI and background noise. The strong alternating current (AC) EMI shown in some of the accelerometers previously has been eliminated through filtering and better facility grounding. The unknown periodical acoustic interferences or vibration detected by accelerometer #3 previously has also disappeared. Besides the SSAS, all of the accelerometers detected some sort of low-intensity vibration during the middle of the test. This indicates that, compared to the accelerometers, the SSAS is less affected by vibration in the facility environment. The prototype failed to resonate continuously. The resonance became weaker, then quickly diminished when the prototype's temperature approached its operating temperature.

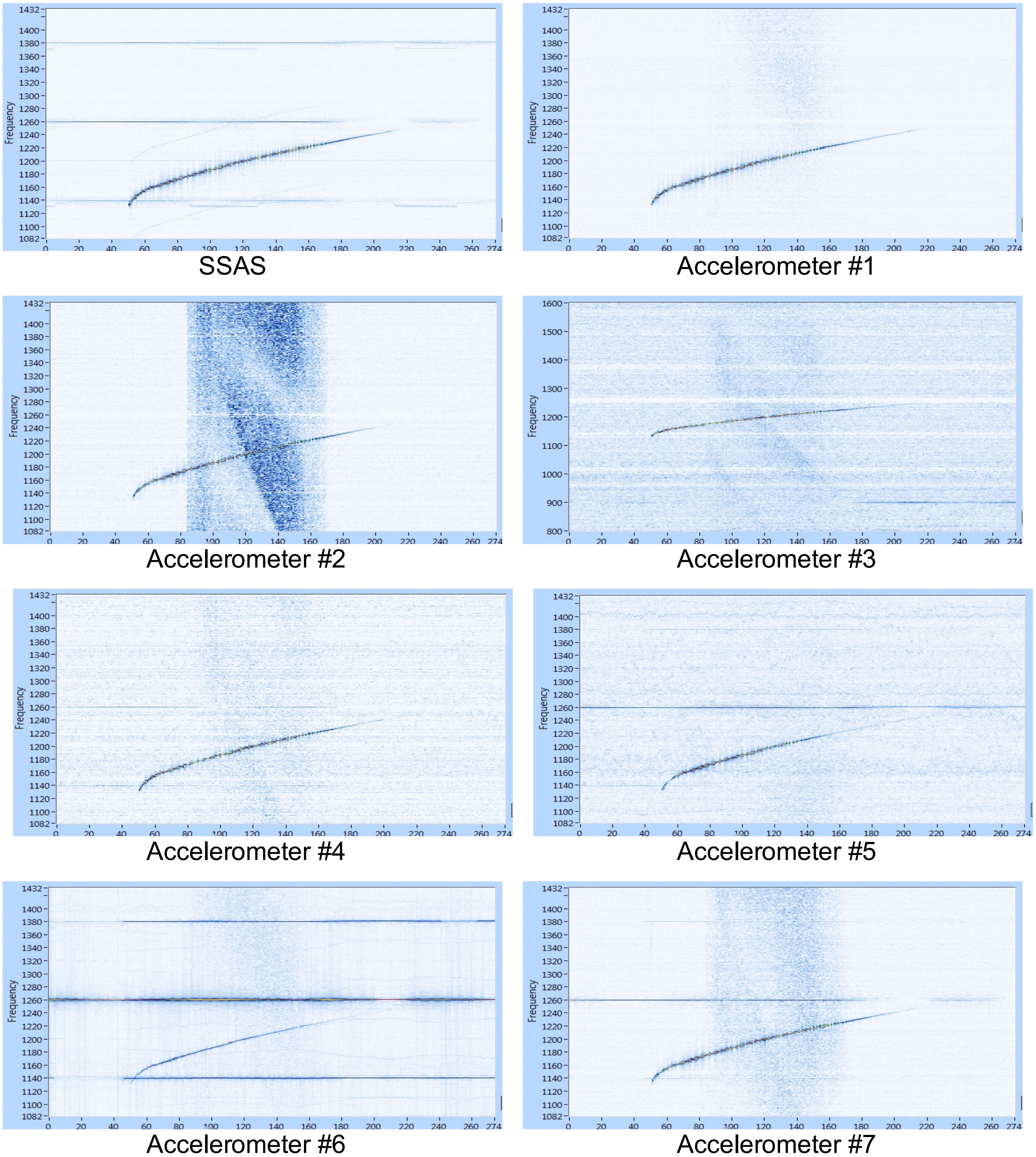


Figure 16. Postprocessed spectrograms acquired by SSAS and accelerometers in solid sodium at 45.2°C.

5.2.2 In-Sodium Test of TAPS in Molten Sodium

In-sodium tests of the TAPS prototype were conducted in molten sodium at a bulk temperature of 128.4°C with the DC power supply of the TAPS's internal heater set at 13.1V and 4.86A. Figure 17 shows TAPS and sodium temperatures, resonance, and spectrograms, acquired by the SSAS in real time. When reaching above ~336°C, the prototype started to resonate at a frequency of ~1,266.7Hz. The resonance frequency rose linearly with the TAPS's temperature, but stopped resonating when the temperature was above

~422°C. The prototype did not establish a continuous resonance at high temperature or close to its operating temperature. The prototype was then cooled down after turning the power supply off. After being reheated, the prototype started resonating accordingly at about the same TAPS temperature and frequency, but still failed to establish a continuous resonance. Figure 18 shows TAPS resonance frequencies changing with respect to the temperature difference between the TAPS and the bulk sodium of the two consecutive tests in molten sodium. The resonant frequencies of the two tests have the same slopes but are offset by 2Hz. Figure 19 shows postprocessed spectrograms of the TAPS prototype acquired by the SSAS and the seven accelerometers. Somehow, accelerometer #5 and #6 received low-frequency interferences, which had higher intensities and did not get filtered out by both the analog and digital filters that was added into the I&C unit.

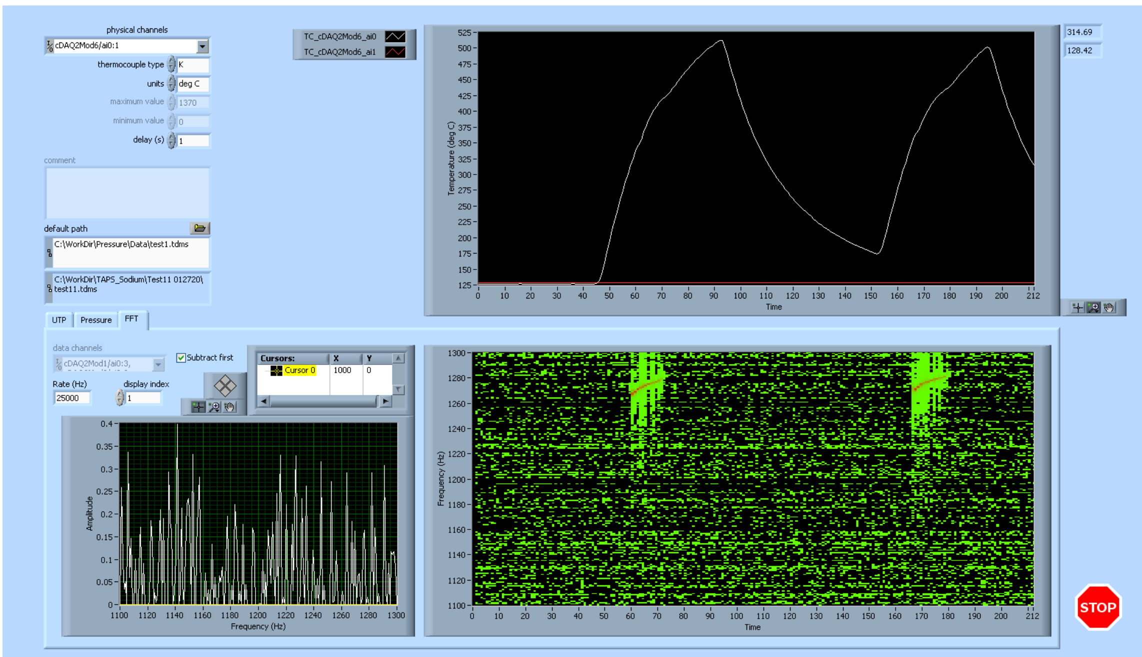


Figure 17. Bulk sodium and TAPS temperatures, spectrogram, spectrum, and resonance of TAPS detected by accelerometer #4 in sodium after postprocessing of test TAPS-LT2.

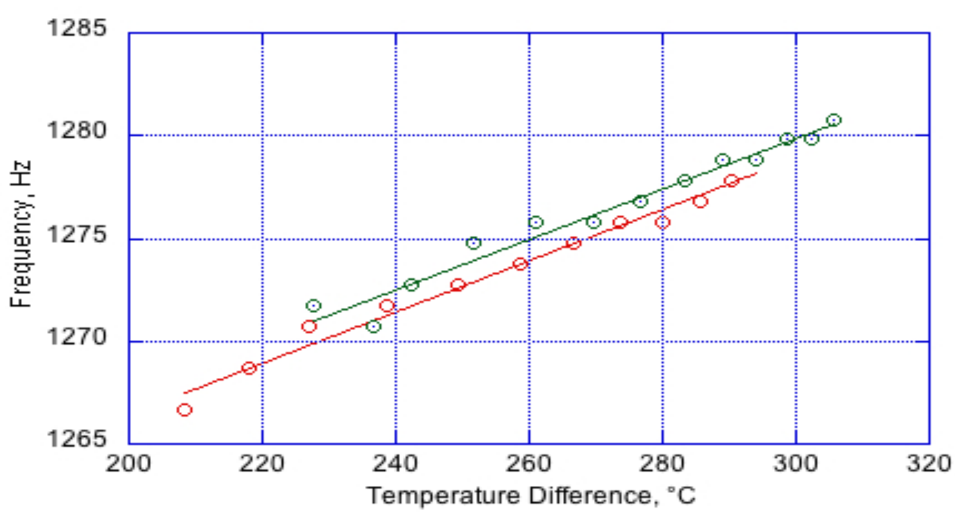


Figure 18. Resonant frequencies of two consecutive tests with respect to temperature difference between TAPS and bulk sodium in molten sodium at 128.4°C.

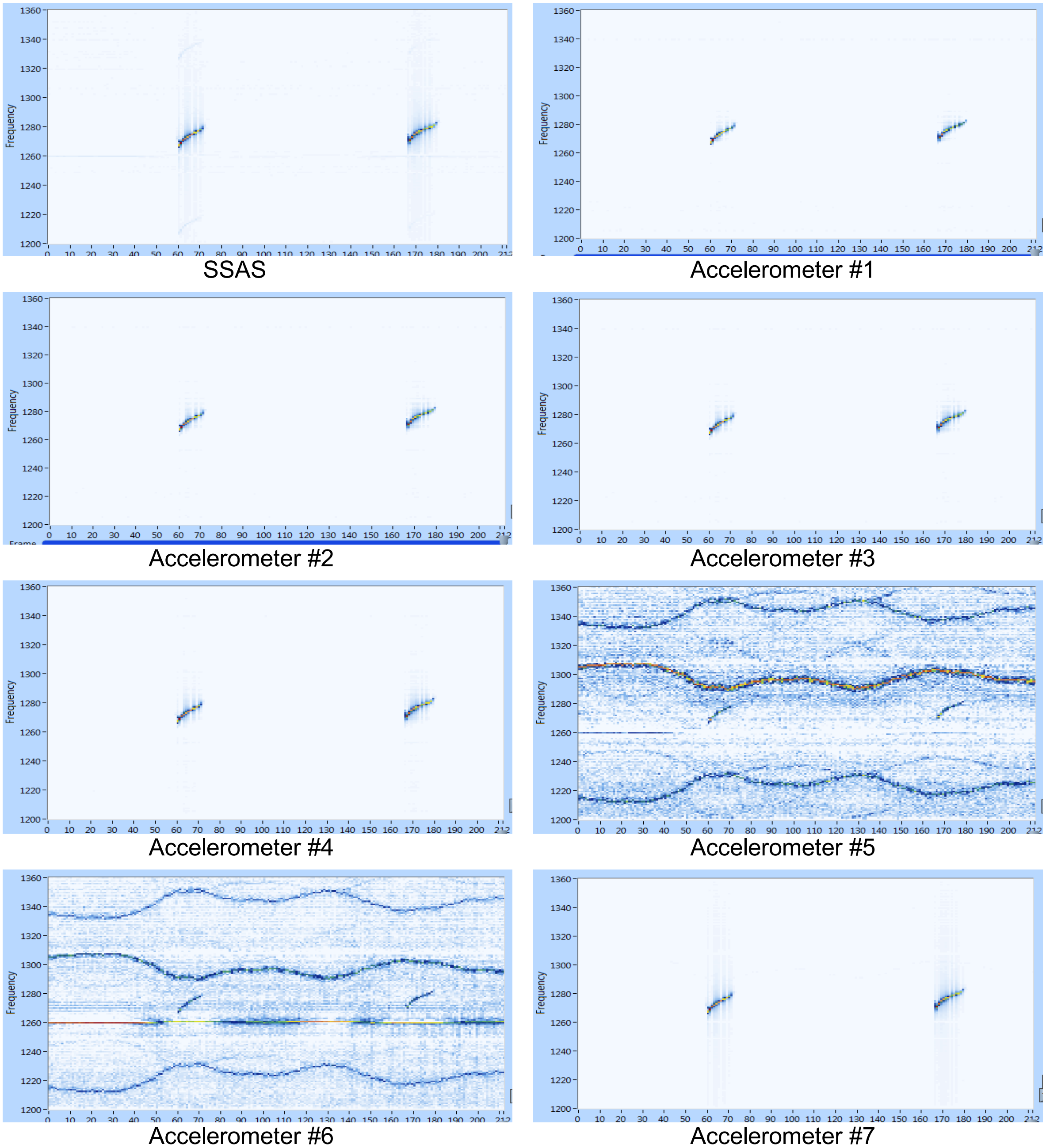


Figure 19. Spectrograms acquired by SSAS and accelerometers in molten sodium at 128.4°C.

5.2.3 In-Sodium Test of TAPS with Continuous Resonance

After immersion in sodium at 167°C (350°F) for several weeks, the TAPS prototype was able to establish a continuous resonance but only in solid sodium. It was suspected that sodium wetting of the TAPS prototype might not have fully developed. A series of tests of the TAPS prototype were conducted in solid sodium at different TAPS operating temperatures, i.e., operating under different DC voltages. Table 2 lists the TAPS operating temperature and quality of resonance intensity of the SSAS and accelerometers of the ten in-sodium tests of the TAPS prototype at 51.5°C. Accelerometers #3 and #6 failed to respond. This might be caused by bonding failures of the accelerometers' mounting bases.

Table 2: Operating Condition and Signal Quality of TAPS Tested in Sodium

File Name	T (°C)	Continuous Resonance	Acoustic Sensor	Accel. #1	Accel. #2	Accel. #4	Accel. #5	Accel. #7
TAPS-LT	50-350	Yes	Good	Fair	X	Good	X	Poor
TAPS-LT1	50-300	Yes	Good	Fair	Poor	Good	Poor	Fair
TAPS-LT2	50-300	Yes	Fair	Good	Fair	Good	Poor	Fair
TAPS-LT3	50-500	X	X	X	X	X	X	X
TAPS-LT4	50-500	No	Poor	Poor	X	Fair	X	X
TAPS-LT5	50-425	Yes	Good	Poor	X	Poor	X	X
TAPS-LT6	50-400	Yes	Fair	Poor	X	Fair	X	X
TAPS-LT7	50-400	Yes	Good	Poor	X	Poor	X	X
TAPS-LT8	50-400	Yes	Poor	Poor	X	Fair	X	X
TAPS-LT9	50-400	Yes	Fair	Poor	X	Fair	X	X
TAPS-LT10	50-400	Yes	Fair	Poor	X	Good	X	X

Test TAPS-LT1 was the first in-sodium test of the TAPS prototype that could establish a continuous resonance. It also repeatedly established continuous and consistent resonances when cycling its controlling DC voltage, i.e., operating temperature. For an unknown reason, comparing with the previous tests, the resonant frequency of the TAPS prototype shifted higher to 1,940Hz or even 2,040Hz in two tests. Figure 20 shows TAPS TC and bulk sodium temperatures, spectrogram, and spectrum of the TAPS acquired by the SSAS. When the TAPS's DC power supply was turned off and on at the end of the test, the TAPS's temperature dropped and recovered accordingly and its resonance also recovered to the sane frequency. Continuous and consistent resonance was established until the DC power supply was turned off.

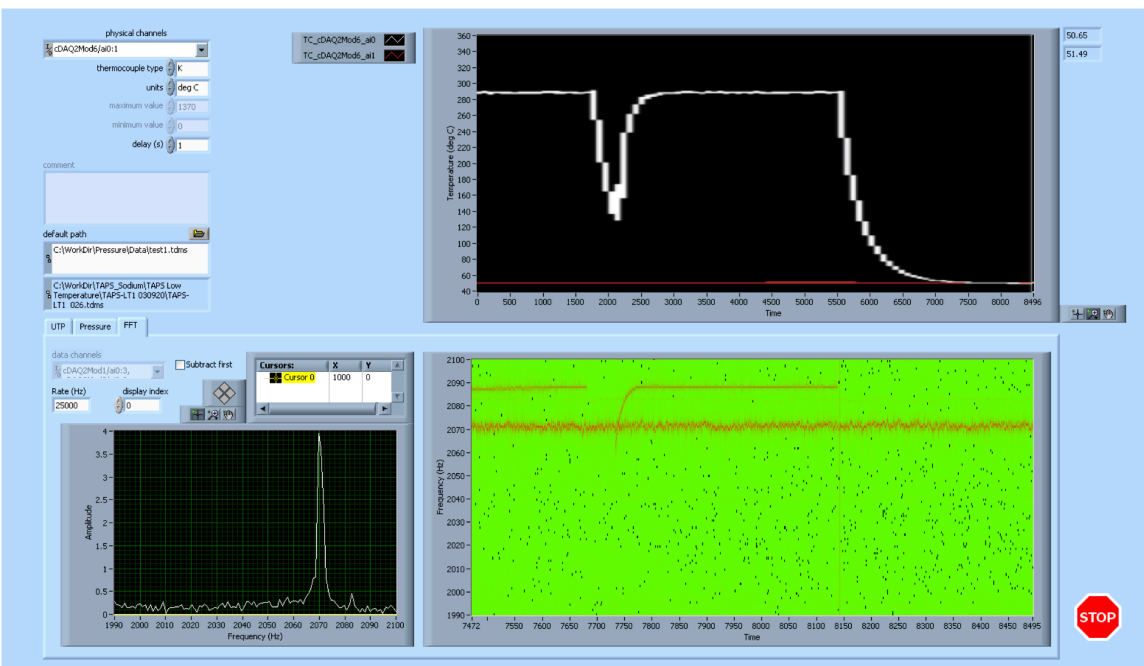


Figure 20. Bulk sodium and TAPS temperatures (top right), spectrum (bottom left), and spectrogram (bottom right) acquired by SSAS in sodium at 51.5°C.

Figure 21 shows TAPS and sodium temperatures, spectrogram, spectrum, and resonance of the TAPS acquired by accelerometer #4 in sodium at 51.3°C after postprocessing of test TAPS-LT2. Figure 22 shows postprocessed spectrograms of the TAPS prototype acquired by the SSAS and three accelerometers (#1, #4, and #7). The TAPS resonance acquired by the SSAS was coupled with acoustic noise in the test environment while that of the three accelerometers was not. From the results shown in Figures 16 and 22, because of the nature of detection principles and mounting methods, the SSAS is more affected by acoustic noise, while accelerometers are more affected by vibrations in the environment. Figure 23 shows postprocessed spectrograms of different in-sodium tests of the TAPS prototype acquired by accelerometer #4. Figure 24 shows TAPS resonance frequencies changing with respect to the temperature difference between the TAPS and bulk sodium. The resonant frequencies of the first two tests (TAPS-LT1 and TAPS-LT2) shifted ~100 Hz higher than that of the other six tests.

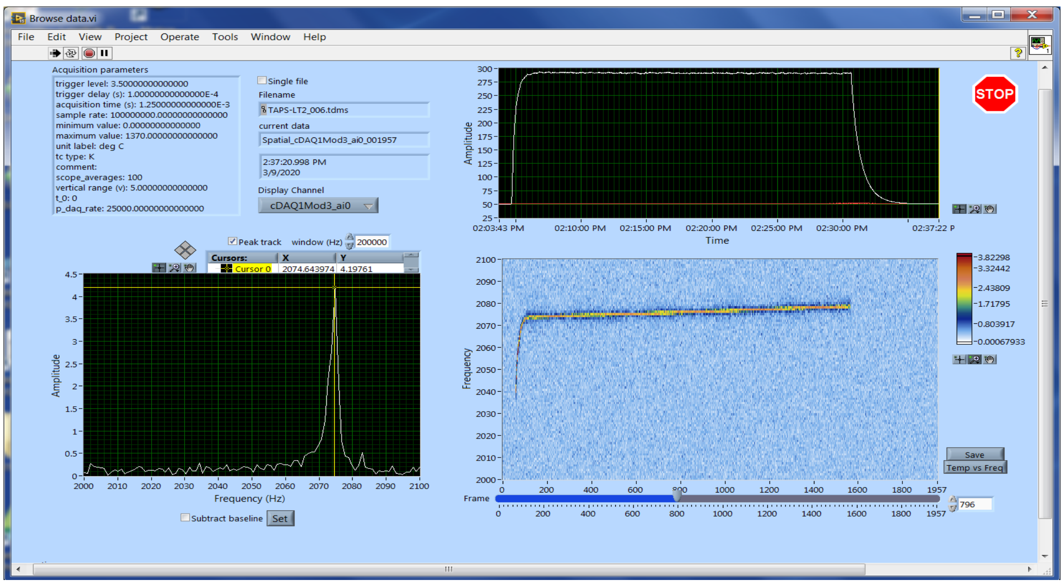


Figure 21. Bulk sodium and TAPS temperatures, spectrum, and spectrogram, of TAPS prototype detected by accelerometer #4 in sodium after postprocessing of test TAPS-LT2.

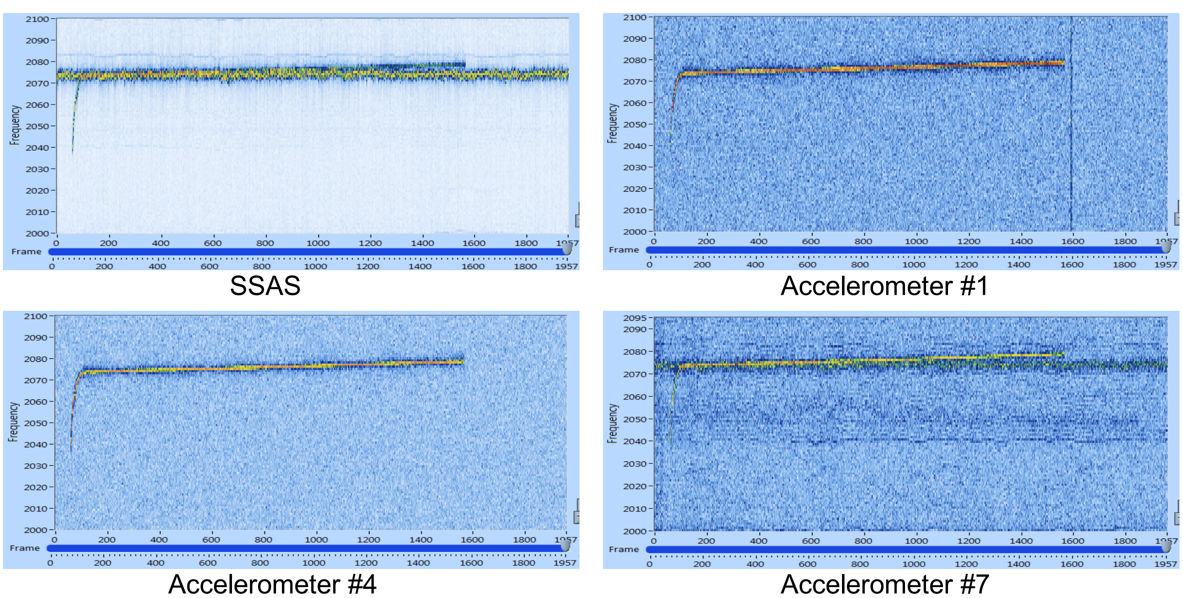


Figure 22. Spectrograms of the TAPS acquired by SSAS and accelerometers of test TAPS-LT2.

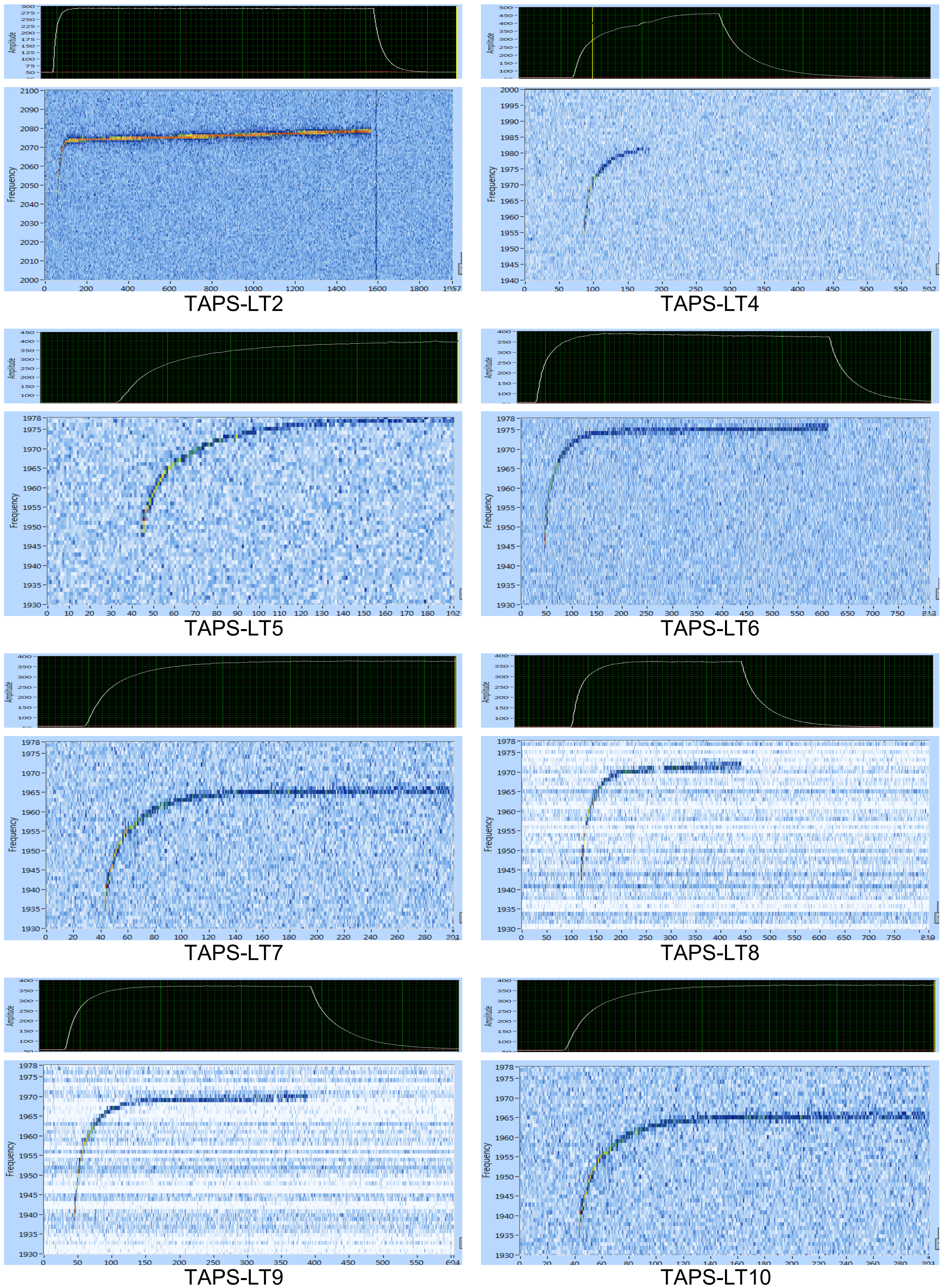


Figure 23. TAPS's temperature and spectrograms acquired by accelerometer #4 for eight different tests in sodium at 51.5°C.

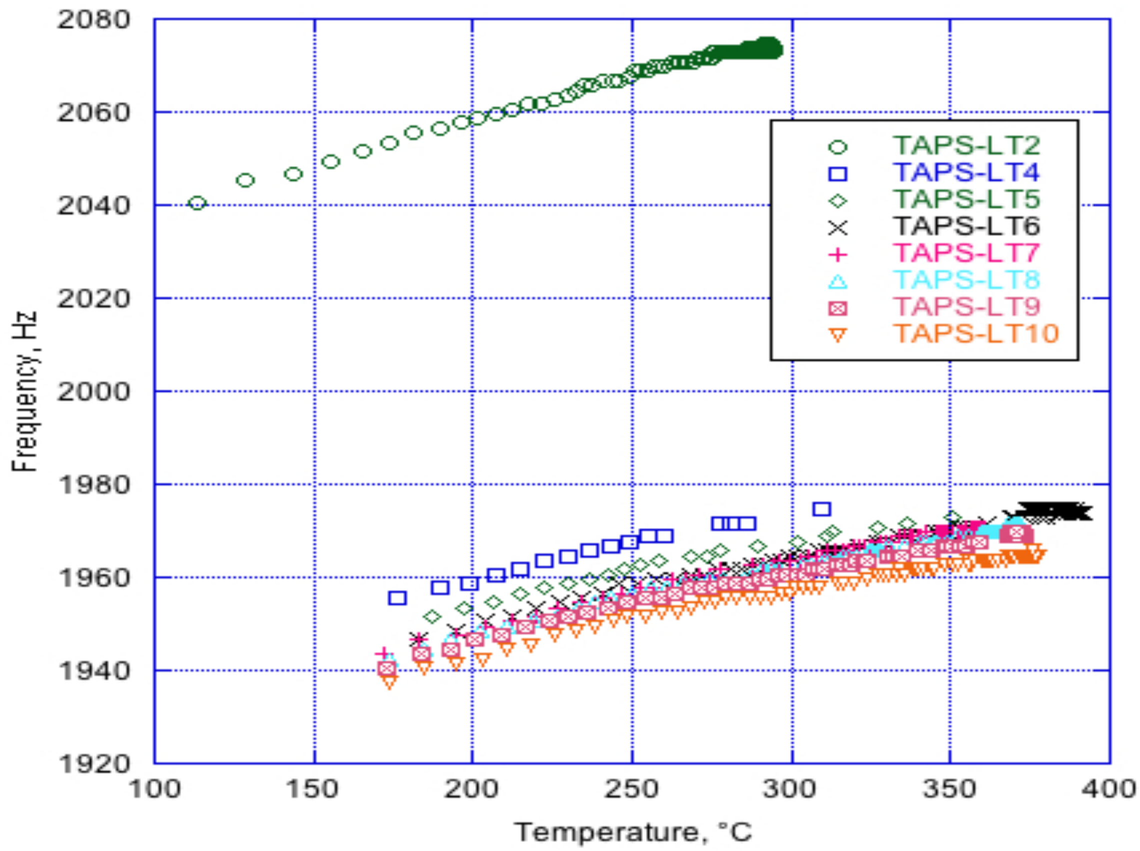


Figure 24. Resonant frequencies acquired by accelerometer #4 of in-sodium TAPS tests.

6 POST IN-SODIUM TESTS AND FAILURE MODES ASSESSMENT

Due to the COVID-19 pandemic and shutdown of most activities at Argonne, the in-sodium testing of the TAPS prototype was suspended for four months. The TAPS prototype was submersed in molten sodium at 149°C (300°F) during the Laboratory shutdown. After the restart of in-sodium testing, the TAPS prototype failed to resonate at all. The TAPS is a passive acoustic resonance device which consists of a resonator filled with helium-argon gas mixture, a heating element with a TC, a thermal insulator at the hot-end, and a ceramic stack. From a failure modes assessment, potential causes of the failure were identified as the following:

a) <u>Too small temperature difference:</u> The prototype generates acoustic waves when the temperature difference between its hot and cold ends is greater than 150°C. If the heat conducted from the hot end to the cold end can't be removed fast enough, causing the temperature gradient to decrease, the resonance intensity would become weaker. Alternately, the TAPS with its internal heater is a localized heat source inside of the bulk sodium inside of the test vessel. As that heat source increases, it is expected to give rise to increasing natural convection of the bulk sodium upward along the TAPS. The convecting sodium may remove heat from the TAPS tending to lessen the temperature difference from the top to the bottom of the ceramic stack. When the temperature difference across the stack drops to a certain level, the resonance would diminish;

b) <u>Ceramic stack broken or blocked:</u> The ceramic stack functions as a thermal insulator to maintain a temperature gradient between the hot and cold ends, as well as guiding the thermoacoustic waves to oscillate between the hot and cold ends. If it is broken or blocked, the waves can't oscillate across the stack and produce standing thermoacoustic waves.

c) Gas leaking out: The prototype is filled with a helium/argon gas mixture (80/20 ratio). Helium has very high thermal conductivity. If the gas mixture or helium in the gas mixture leaks out as by leakage through a seal or diffusion through the TAPS wall, then the gas density would drop and might weaken or stop the standing thermoacoustic wave oscillation. Preferential diffusion of helium through the seal or TAPS wall would reduce the gas thermal conductivity.

d) Heater failure: The prototype uses an electric heater as a heating source to maintain a consistent operating temperature at the hot end, i.e., to generate a consistent resonant frequency. If the heater fails to produce a consistent heating, the standing thermoacoustic wave oscillation might be weakened or diminished completely.

To obtain further information potentially relevant to the cause of the failure, different post in-sodium tests have been conducted.

Post In-sodium Test in Cover Gas

The TAPS prototype was tested in cover gas before submersing into sodium. As presented in Section 5.1, the prototype was able to generate a continuous and consistent resonance at 1407.2 Hz when operating at 590°C. The test vessel has an extension cap mounting on the top flange such that the prototype can be lifted out of the liquid sodium and removed from the test vessel. To assess the cause of the failure, the first post in-sodium test conducted was to lift and test the prototype in cover gas. Unfortunately, operating at different TAPS operating temperatures, the prototype did not resonate at all in cover gas at 149°C (300°F).

Post In-sodium Test in Water

Since the prototype did not resonate in cover gas, we decided to remove it from the test vessel and test it in water. The sodium in the test vessel was drained into the dump tank. After the vessel cooled down, the extension cap was then covered inside a glove bag that was filled with argon gas to avoid sodium contamination while removing the cap flange and the prototype. The prototype was put inside a metal pipe in the scrub room for several days. After the residual sodium hydrated, the prototype was submersed in alcohol and cleaned with acetone. The prototype was tested in distilled water. It still did not resonate.

Internal and External Integrity Examination

By examining the exterior of the prototype, we did not find any damage. However, there is some kind of rattling sound when turning it upside down. An x-ray of the prototype might be able to examine its internal integrity. The seal location where the helium-argon gas mixture could leak out is through the heater and TC lead connection ports. It is not possible to examine the ports unless the SS protection tube is cut off. An alternative is to measure the speed-of-sound by using an ultrasonic technique to determine the gas composition of the gas mixture.

Heater diagnosis

The prototype was operated with a consistent DC power supply setting (13.1V and 4.93A). The operating temperature of the hot end attained over 500°C. During the post in-sodium test in water, the operating temperature could only reach ~300°C, which theoretically should generate a temperature gradient that is large enough to initiate a resonance, but it didn't.

7 DISCUSSION AND SUMMARY

Argonne completed the construction of a TAPS test apparatus and successfully integrated it with the upgraded USV sodium test facility. The integrated USV-TAPS sodium test facility has been operational for in-sodium testing of the TAPS. Argonne received a TAPS prototype from Westinghouse and the prototype was modified such that it can be installed into the TAPS test vessel and work in sodium at elevated temperature without potentially causing sodium leaking. The prototype and a high-temperature sodium-submersible acoustic sensor (SSAS) developed by Argonne were both installed inside of the TAPS test vessel. Ten accelerometers were also mounted on the external wall and the top flange of the TAPS test vessel. An instrumentation and control (I&C) system was developed for operation of the USV-TAPS facility, as well as data acquisition and analysis. A signal postprocessor was added to the DAQ module to isolate interferences, enhance signal conditioning, improve peak detection, and generate resonance frequency versus temperature plots.

For functionality verification, the TAPS prototype and the SSAS were tested within argon cover gas under ambient conditions. The prototype demonstrated that it was functioning properly with a resonant frequency at 1,407.2 Hz, which was successfully detected by the high-temperature SSAS and all seven accelerometers. After successfully transferring sodium into the test vessel, in-sodium tests of the prototype were conducted at different sodium temperatures. Tests of the TAPS prototype demonstrated that the resonance frequency of the TAPS changes linearly with respect to the temperature difference between the TAPS and bulk sodium. The resonant frequency was lower than that obtained in a water mockup and the cover gas tests. Also, the resonance of the TAPS prototype diminished before the prototype reached its operating temperature and failed to establish a continuous resonance in sodium. After testing in molten sodium and immersion at higher temperature for several weeks, the TAPS prototype was able to establish a continuous resonance but only in solid sodium. The tests also demonstrated that, because of the nature of the detection principles and mounting methods, the high-temperature SSAS is more affected by acoustic noise, while accelerometers are more affected by vibrations, in the test environment.

It is unknown why the TAPS prototype only occasionally established a continuous and consistent resonance when the TAPS temperature reached its operating temperature in molten sodium, and why it ultimately failed to resonate at all. A failure modes assessment was conducted and a few potential causes of failure were identified. Different post in-sodium tests were conducted to obtain additional information potentially relevant to the cause of the failure. Nondestructive evaluation techniques are suggested to examine the internal integrity as well as the gas mixture of the prototype. If they prove inconclusive, the prototype should be cut open to conduct a thorough inspection of its internal integrity and determine the state of the gas mixture.

REFERENCES

1. M. D. Heibel, et. al., “Development of Thermoacoustic Sensors for Sodium-cooled Fast Reactors,” Westinghouse Technical Report RT-TR-18-18, September 2018.
2. H. T. Chien, J. J. Sienick, T. W. Elmer, and W. P. Lawrence, “Demonstration of Thermoacoustic Power Sensor,” Argonne National Laboratory Technical Report ANL-ART-180, September 2019.
3. “Functional Requirements for Thermo-Acoustic Sensor System for Sodium-cooled Fast Reactors,” June 2015, Westinghouse Internal Report, RT-FR-15-001.

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